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AN EXPERIMENTAL STUDY OF THE INFLUENCE OF OBSTRUCTIONS IMMEDIATELY DOWNSTREAM FROM THE TURBINE WHEEL ON TURBINE PERFORMANCE

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota
by
ees ertrand
R. B. SPENCER

In Partial Fulfillment of the Requirements
for the
Degree of
Master of Science
in
Aeronautical Engineering
(Power Plants)
August
1949

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ACKNOWLEDGEMENTS

I wish to express my gratitude to the following members of the faculty of the University of Minnesota for their help in making this thesis possible.

To Professor B. J. Robertson for his guidance and advice in this project.

To Doctor Newman A. Hall and Professor T. C. Murphy for their technical advice and assistance.

To Mr. K. Neumeier for his help in installing the project.

And to Lieutenant F. R. Putnam, U. S. Navy, for his assistance in obtaining the data and running the test equipment.

University of Minnesota

20 August 1949 R. B. Spencer

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AN EXPERIMENTAL STUDY OF THE INFLUENCE OF OBSTRUCTIONS IMMEDIATELY DOWNSTREAM FROM THE TURBINE WHEEL ON TURBINE PERFORMANCE

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SUMMARY

An investigation was conducted on obstructions in the tail pipe of a B-11 Turbosupercharger in order to determine their influence upon the performance of the turbine wheel. The obstructions were located down stream of the turbine wheel at stations varying from 9/16 inch to 3.0 inches. At each station the turbosupercharger was run at speeds varying from 10,000 to 20,000 revolutions per minute. The expansion ratios across the turbine varied from 1.17 to 1.70. At each speed the turbine input power and the compressor input power were measured. The efficiencies were computed by the ratio of compressor power to turbine power.

Two types of obstructions were employed. One was a set of four 1½ inches in diameter rods 2½ inches long, and the other was a set of four sectors with a 7 inch outer radius and a 4½ inch inner radius. Each sector was ½ inch thick.

At the speeds, expansion ratios, and the air flows used in this investigation no change in turbine performance was observed.

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INTRODUCTION

This project was conducted to determine the influence of obstructions immediately downstream from the turbine wheel upon the performance of the turbine. Two types of obstructions were employed in this investigation. The distance from the turbine wheel at which the obstructions were located was varied as well as the speed and the expansion ratio of the turbine. The effect of these obstructions was obtained by computing the efficiency from the turbine power input.

This project was instigated by the desire to know whether obstructions would influence the performance of a gas turbine and the amount of the influence. In gas turbine design the tail pipe lends itself readily to the adaptation of preheaters, regenerators, and other heat absorbing devices. Also, in certain type jet engines employing variable tail pipe nozzles, the mechanism which controls the variable nozzle is located within the tail pipe. In turbopropeller design it would be advantageous to divide the exhaust pipe or to bend the flow of the exhaust. In employing after

burning the after burners are located within the tail pipe. In any of the foregoing situations what is done is equivalent to obstructing the tail pipe. Therefore this investigation has contributed to advancing the design of turbojet and gas turbine engines.

This investigation was not conducted to check or to determine the performance of a gas turbine, nor was it instrumented to do so. The turbine employed was instrumented only to determine the power input and output at existing ambient conditions.

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EQUIPMENT AND PROCEDURE

The turbosupercharger used in this investigation was a B-33, manufactured by the Allis-Chalmers Company under license from the General Electric Company. The compressor was rated at 120 pounds of air per minute at an altitude of 2,500 feet and at a speed of 24,000 revolutions per minute. The turbine was a single stage impulse turbine with all the pressure drop occurring across the nozzles. The turbine air was supplied by the supercharger of an Allison V-1710 aircraft engine. The Allison engine was naturally asperated. A Jumo 004 type combustion chamber was attached to the turbine and the air from the Allison engine was burned to approximately 1775 degrees Rankine before entering the turbine. The best operating expansion ratio for the turbine was used between 3 and 4, with the waste gate partially opened depending on the power required by it. In this investigation the waste gate was sealed closed.

Ambient air from outside the laboratory was drawn in by the compressor, compressed, and then discharged back outside the building. The air used for the turbine

was picked up inside the test cell, compressed in the supercharger of the Allison engine, passed through the combustion chamber, through the turbine and then discharged outside the building.

The tail pipe used was manufactured at the metal shop of the University of Minnesota and was constructed of stainless steel. The tail pipe consisted of an inner and an outer pipe. The outer pipe was 14 inches in diameter. It was provided with a flange so that it could be bolted to the turbine discharge flange. It was also provided with four equally spaced longitudinal slots 10 inches long and 1/8 inches wide. These slots were used to position the obstructions in the tail pipe. The inner pipe consisted of a cylindrical pipe 9 inches in diameter and one foot long to which was welded a cone one foot long. The inner pipe was held rigidly in place by three struts two inches in diameter. These struts were 14 inches from the turbine wheel. One strut was adapted to pass cooling air to the inside of the inner pipe. The air passed upstream from this strut and impinged upon the downstream side of the turbine wheel. The cooling air was forced in at about ten pounds per minute. The cooling air was picked up inside the test cell.

The forward ten inches of the tail pipe was the test section. The test obstructions were placed transversally between the inner and the outer pipes. When

the obstructions were in place, the slots in the outer pipe were closed by four plates 1½ inches long and two inches wide. The plates were curved to conform to the contours of the outer pipe. The forward ends of the slots were drilled for a ¼ inch stud. The stud was passed through the hole in the plate, through the slot, and then screwed into the test obstruction. This provided the means of securely holding the obstruction in place. The after end of the plates were held in place by a metal clamp which passed all the way around the tail pipe. Separate plates were used for each test location.

Two types of obstructions were employed. One type was four 1¼ inch diameter rods 2½ inches long. The ends of the rods were shaped to conform to the contours of the inner and outer pipes. The ends which fitted against the outer pipe were drilled and tapped for a ¼ inch stud. The other type was four 30 degree sectors with a seven inch outside radius and a 4½ inch inside radius. Each sector was ½ inch thick and when all four sectors were in place one-third of the tail pipe was obstructed. The outside edge of the sectors were drilled and tapped to accommodate the ¼ inch studs. These studs were used to hold the test obstructions in place as described above.

The 1¼ inch diameter rods were used first in this investigation. They were placed first at a distance of three inches downstream of the turbine wheel and

then were moved upstream at one inch increments. At each station the turbine was run at 10,000, 12,000, 14,000, 16,000, 18,000, and 20,000 revolutions per minute. At each station and each speed the power input to both the compressor and the turbine was measured. The turbine efficiency was computed by dividing the compressor power by the turbine power. At one inch from the turbine wheel it was observed that no effect from the obstructions existed and at this time the study was started on the sector obstructions. The sectors were placed as close to the turbine wheel as possible which was 9/16 inch. This distance was limited by a flange around the turbine discharge which protruded 9/16 inch from the turbine wheel. It was also felt that any closer distance would endanger the turbine wheel in case of vibrations being set up in the obstructions. On the run at 9/16 inch from the turbine wheel two bolts securing the tail pipe to the turbine backed out.

The following is a list of runs that were made. Each set of runs was made at 10,000, 12,000, 14,000, 16,000, 18,000, and 20,000 revolutions per minute.

Set No.	Type Obstructions	Location
1	None	None
2	$1\frac{1}{4}$ inch rods	3.0 inches
3	$1\frac{1}{4}$ inch rods	2.0 inches
4	$1\frac{1}{4}$ inch rods	1.0 inches
5	None	None

Set No.	Type Obstructions	Location
6	30 degree sectors	9/16 inches
7	30 degree sectors	1.0 inches
8	30 degree sectors	9/16 inches

List of test equipment:

1. B-33 Turbosupercharger

   Manufactured by Allis-Chalmers under contract from the General Electric Company.

2. Jumo 004 Combustion Chamber

   Manufactured in Germany for the Jumo 004 Turbojet engine.

3. Fuel Pump Motor

   Manufactured by the Siman Company.

4. Fuel Pump

   Manufactured by the Vickers Inc., Company.

5. Ignition Coil and Spark Plug

   Made in Germany for the Jumo 004 engine.

6. Acetylene Supply.

7. Allision V 1710 aircraft engine, naturally aspirated.

8. Allision V 1710 supercharger.

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INSTRUMENTATION

The instruments used in this investigation were previously installed and supplied by the University of Minnesota. No effort was made to calibrate these instruments. The measurements taken were not to determine the performance of the turbosupercharger, but rather to measure variations in the performance. The instruments used were considered adequate to conduct this investigation.

The air flow to the turbine was measured by a 5.6 inch diameter flat plate orifice in an eight inch pipe. Flush type pick-ups were used to measure the differential pressure. One was located eight inches upstream of the orifice and the other was located four inches downstream of the orifice. This differential pressure was read on a six inch inclined mercury manometer which could be read to the nearest five hundredths of an inch. This orifice was previously calibrated and was assumed accurate throughout the investigation. The air flow to the compressor was measured by a seven inch diameter orifice. This orifice as well as the calibration charts

were obtained from the Packard Motor Car Company, Aircraft Engine Division. The differential pressure was read on a 20 inch water vertical manometer. This orifice was previously calibrated and was assumed accurate throughout the investigation.

The temperatures of the air flows through both orifices were measured by a self balancing potentiometer used with an iron constantan thermocouple. The self balancing potentiometer was manufactured by the Brown Instrument Company, and hereinafter is referred to as a Brown Box. This instrument could be read to the nearest five degrees Fahrenheit. Hence, measurements taken at low temperatures are subjected to more error percentage wise than temperatures of a higher order.

The fuel flow was measured with a Stabil vis Rotameter manufactured by the Fischer Porter Company. This instrument was designed for a diesel fuel of specific gravity of .852. The fuel used in this investigation was a fuel oil and its specific gravity did not vary over five per cent from that for which the instrument was designed.

Temperatures were measured at the compressor inlet and outlet, and at the turbine inlet and outlet. These temperatures were measured with the Brown Box. To measure the turbine inlet temperature a chromel alumel thermocouple was used. This thermocouple was located one-quarter the distance around the nozzle box from the

turbine air inlet. This location was chosen in order to keep the thermocouple out of the direct flame from the combustion chamber. A calibration chart for the use of the chromel alumel thermocouple is appended to this report. The other temperatures were measured with the Brown box using 20 gauge iron constantan thermocouples.

List of instruments:

Manometers

1.	P_{c1}	Mercury Barometer
2.	P_2	Aneroid 10- 54 inches Mercury
3.	P_3	Vertical 57 inches Mercury
4.	P_{t1}	Aneroid 10- 54 inches Mercury
5.	P_{t4}	Vertical 70 inches Mercury
6.	ΔP_c	Vertical 20 inches water
7.	ΔP_t	Inclined 6 inches Mercury

Temperatures

8.	T_{c1}	Bare I C thermocouple
9.	T_2	Bare I C thermocouple
10.	T_3	Bare I C thermocouple
11.	T_{t1}	Bare I C thermocouple
12.	T_{T4}	Shielded C A thermocouple

Tachometer

13.	Turbine RPM	Synchronous motor 0-35,000 RPM

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RESULTS AND DISCUSSION

The results of this investigation are found in Tables XIII through XVII and Figures 7 through 9. The obstructions used in this investigation produced negligible results on the turbine performance. The computed changes in turbine efficiency are erratic and variable. However, the overall trend is to show that no change in efficiency when as much as one-third of the tail pipe was obstructed. The erratic readings are a direct result of the irregular output of the Allision supercharger. At the low manifold pressures used on the Allision engine during the investigation it was impossible to maintain steady operating conditions on this engine. Its speed would vary as much as 200 revolutions per minute for a fixed throttle setting. Consequently, the supercharger was varying and surging in its output. This surging caused uneven burning of the air in the combustion chamber which caused temperature variations at the nozzle block. The total entrance temperature to the turbine is believed to be in considerable error due to the surging of the Allision supercharger.

When the turbosupercharger was running at 20,000 revolutions per minute the Allison engine was running near its maximum rated speed. Above 18,000 revolutions per minute on the turbosupercharger it was impossible to cool the Allison engine and its oil. This was due to an inadequate cooling water supply. The data taken at 18,000 and 20,000 revolutions per minute was taken very quickly and during changing conditions. Consequently, the data at these speeds are questionable.

The maximum efficiency of the turbine at its rated air flow occurs at an expansion ratio of about three. The maximum expansion ratio reached in this study was 1.70. Higher values could not be obtained because of the limitations of the Allison engine and its supercharger. If higher values could have been obtained this investigation would have been more complete in its scope.

The efficiency as obtained by this study are unreliable. As stated previously the total entrance temperature is believed to be in error. Since efficiency is an inverse function of this temperature, a variation in this temperature will cause an inverse variation in the efficiency. However, this investigation was conducted to measure differences in efficiencies only, and the differences should be accurate within experimental accuracy.

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CONCLUSION

This investigation has shown that obstructions placed in the tail pipe of a gas turbine has negligible effect upon the efficiency of the turbine. Large obstructions placed relatively close to the turbine wheel showed no noticeable change in the turbine efficiency.

It is recommended that further study be made on this project, employing a different type tail pipe and a different type method of measuring the turbine power output. It is suggested that a tail pipe be used whose outside diameter is the same as the outside diameter of the turbine wheel, and that the inside pipe have the same diameter as the root circle of the turbine blading. Such a tail pipe will prevent any expansion of the exhaust gases between the turbine wheel and the obstructions. This type pipe would also maintain higher velocities around the obstructions in the tail pipe. It is further recommended that some type of dynamometer be used to absorb the turbine power rather than its compressor. This would eliminate temperature and pressure errors in the computation of the power.

AN EXPERIMENTAL STUDY OF THE INFLUENCE OF OBSTRUCTIONS IMMEDIATELY DOWNSTREAM FROM THE TURBINE WHEEL ON TURBINE PERFORMANCE

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FORMULA

1. Table of Symbols.

P_{c1}	Static pressure of the compressor measuring orifice. (inches of Mercury)
P_2	Static pressure of compressor inlet. (inches of mercury relative)
P_3	Static pressure at discharge of compressor. (inches of Mercury relative)
P_{t1}	Static pressure of the turbine measuring orifice. (inches of Mercury relative)
ΔP_c	Differential pressure across the compressor measuring orifice. (inches of water)
ΔP_t	Differential pressure across the turbine measuring orifice. (inches of Mercury)
P_{T4}	Total pressure at turbine entrance. (inches of Mercury)
P_{T5}	Total pressure at turbine exit. (inches of Mercury)
T_{c1}	Temperature at the compressor measuring orifice. (degrees Rankine)
T_2	Temperature at compressor inlet. (degrees Rankine)
T_3	Temperature at Compressor exit. (degrees Rankine)
T_{t1}	Temperature at the turbine measuring orifice. (degrees Rankine)
T_{T4}	Total temperature at turbine inlet. (degrees Rankine)
T_{T5}	Total temperature at turbine exit. (degrees Rankine)

W_c Air flow through the compressor. (pounds per minute)

W_t Air flow through the turbine. (pounds per minute)

L_c Power input to the compressor. (B.T.U. per minute)

L_t Power input to the turbine. (B.T.U. per minute)

B.T.U. British Thermal Unit.

γ Ratio of specific heat at constant pressure to specific heat at constant volume.

η_t Turbine efficiency.

H_T Total enthalpy.

Q Heat added.

W Work.

g Acceleration of gravity.

J Mechanical equivalent of heat.

C_p Specific heat at constant pressure.

V Theoretical spouting velocity. (feet per second)

2. Power and Efficiency.

$$L_c = W_c \; C_p \; T_{T2} \; \frac{T_{T3} - T_{T2}}{T_{T2}}$$

$$L_t = W_t \; C_p \; T_{T4} \left[1 - \frac{1}{\left(\frac{P_{T4}}{P_{T5}}\right)^{\frac{\gamma - 1}{\gamma}}} \right]$$

$$\eta_t = \frac{L_c}{L_t}$$

3. Spouting Velocity.

$$V = \sqrt{2gJ \; C_p \; T_{T4} \left[1 - \frac{1}{\left(\frac{P_{T4}}{P_{T5}}\right)^{\frac{\gamma - 1}{\gamma}}} \right]}$$

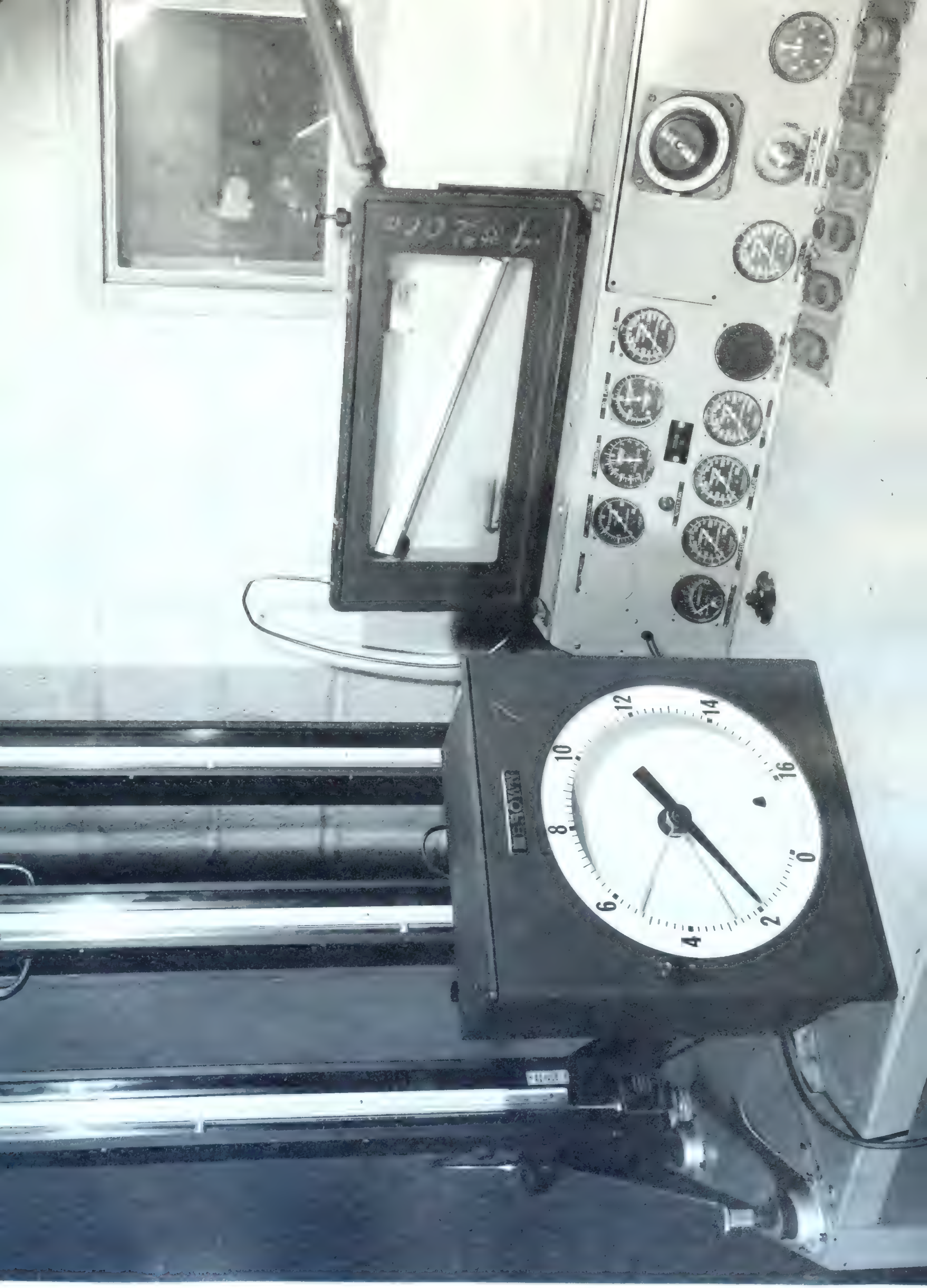


Plate I. Brown Self Balancing Potentiometer.

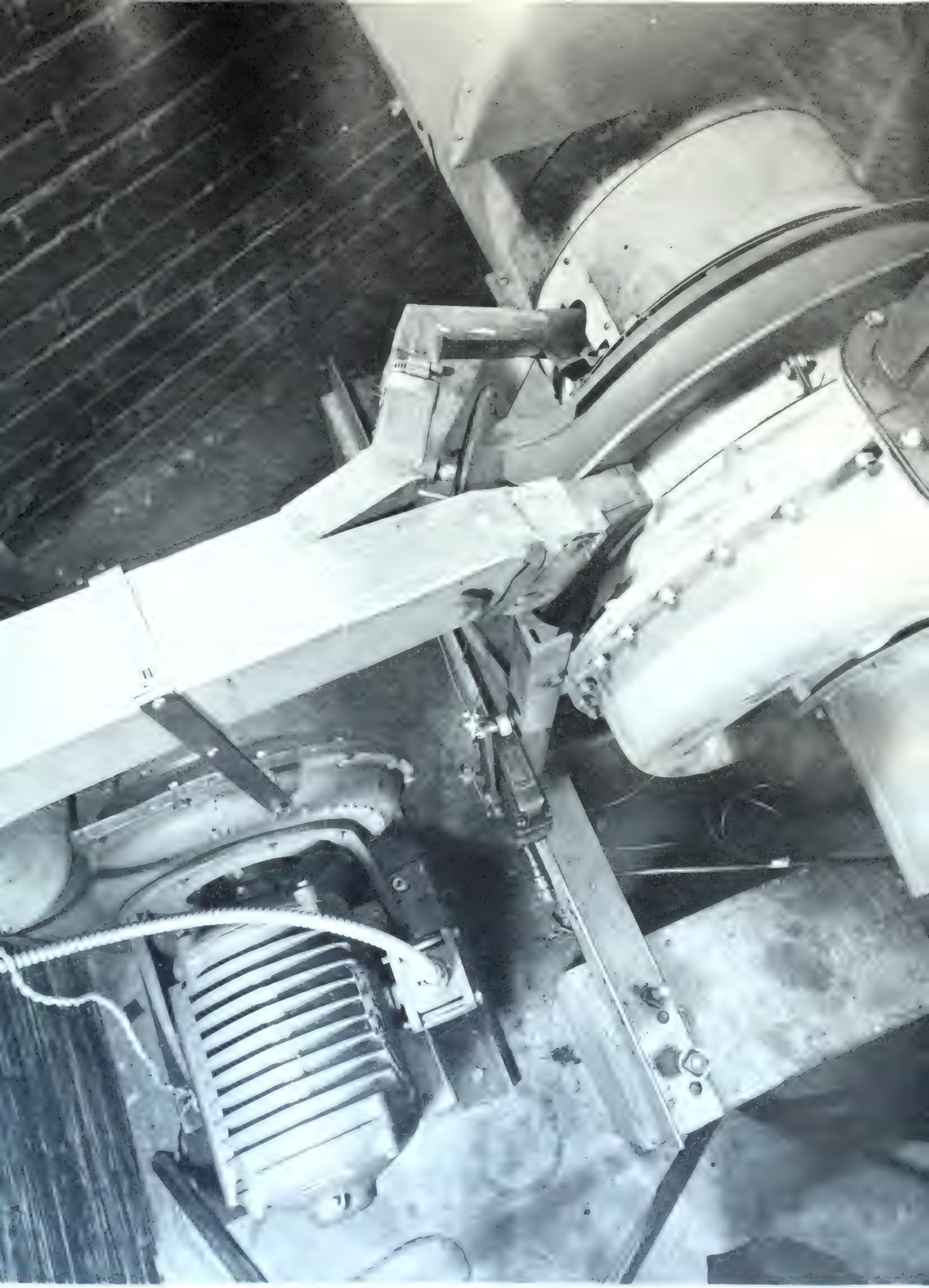


Plate [illegible], Cooling Air Fan, Motor,and Ducting.

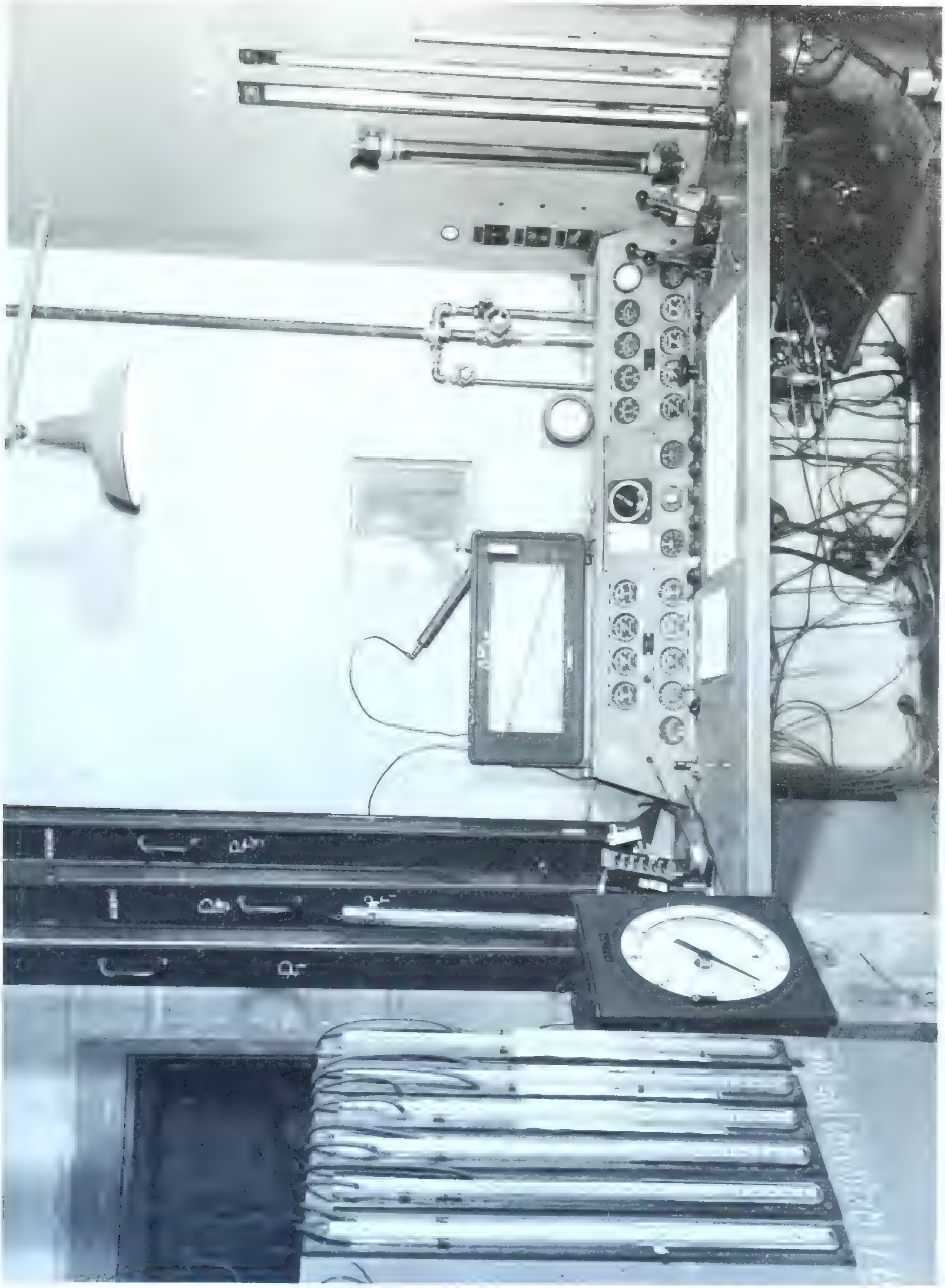


PLATE III. Instrument Panel.

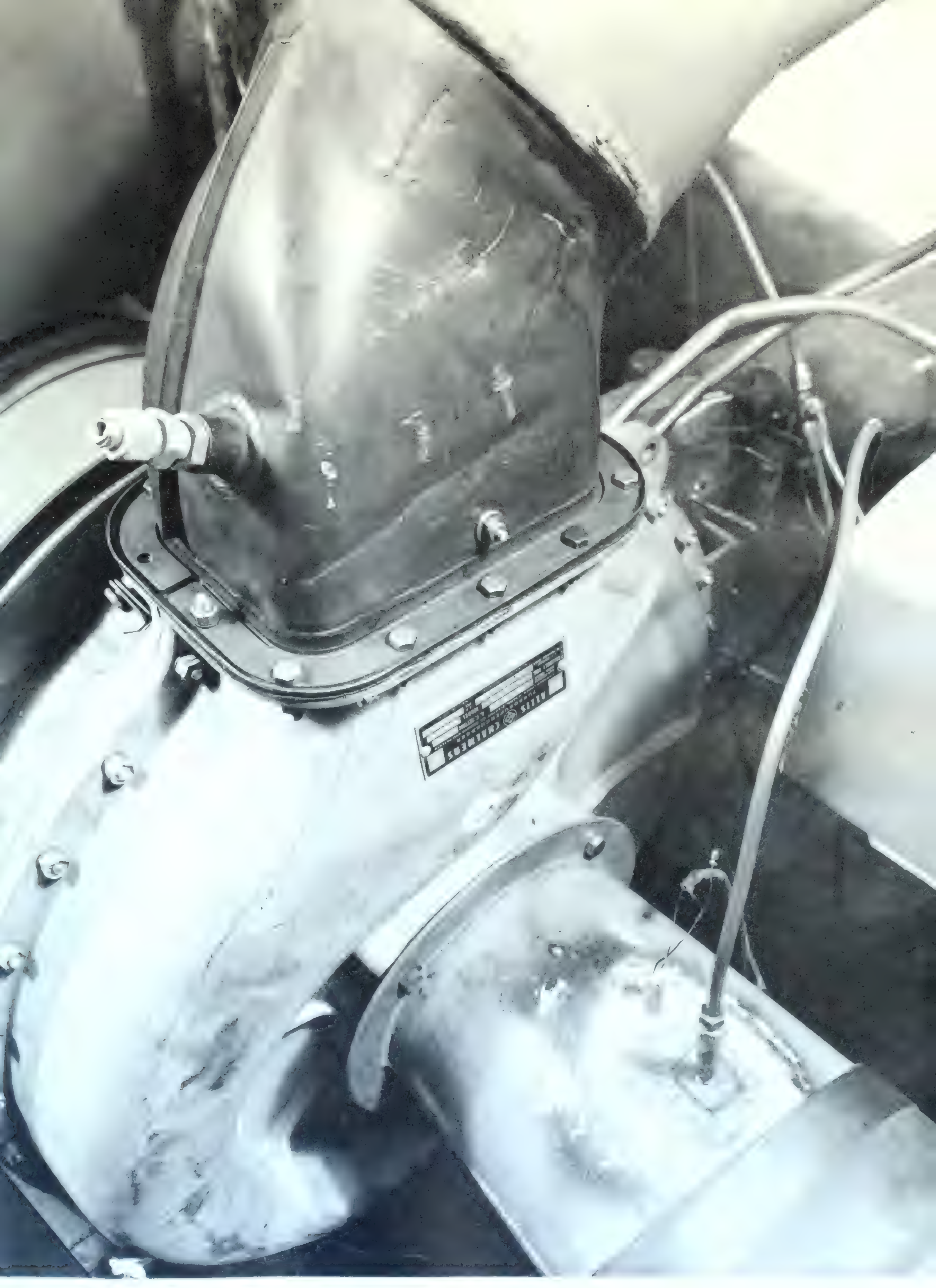
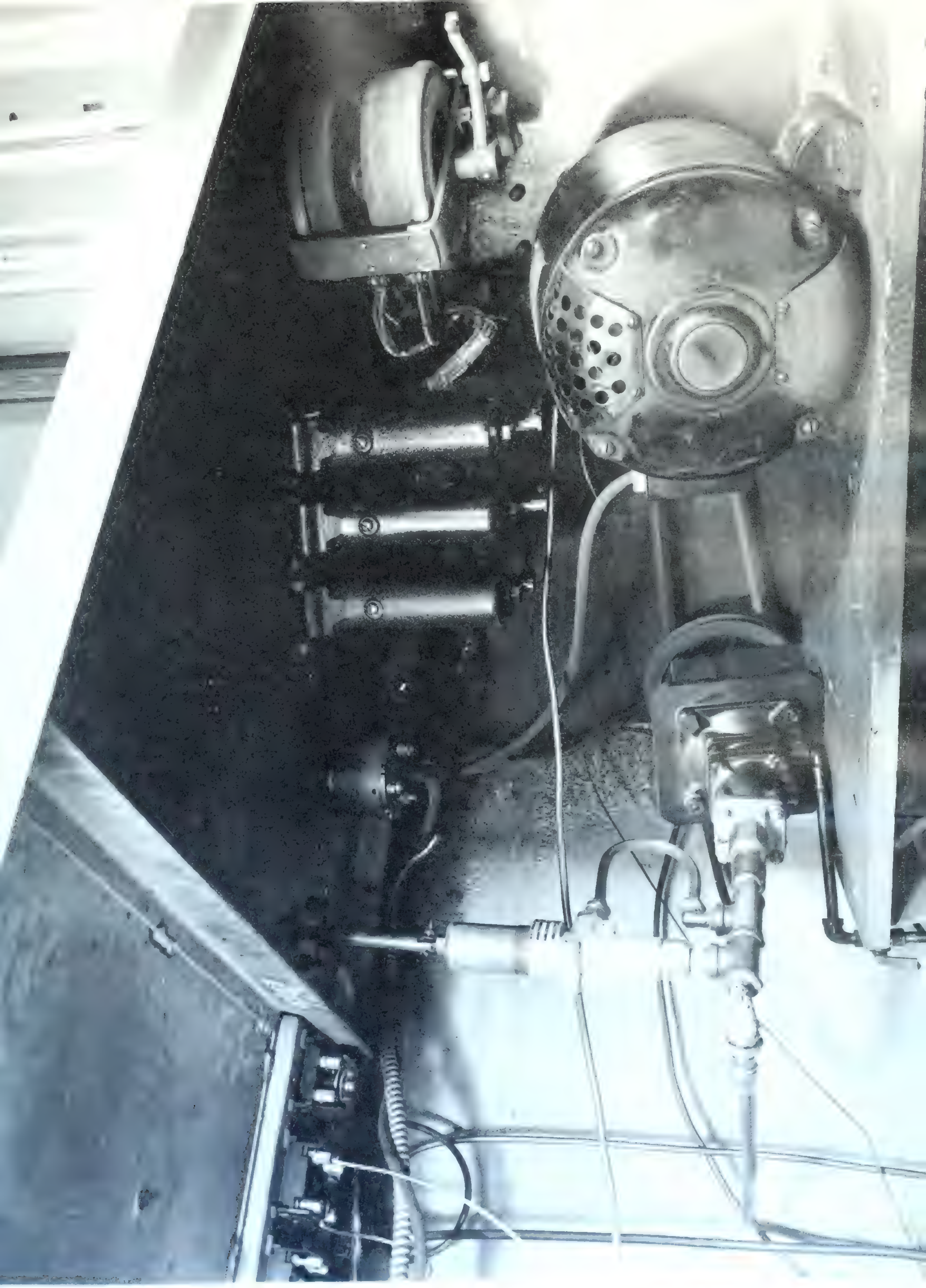


Plate 7. Compressor Inlet Instrumentation.



Station 1, [illegible] Pump, [illegible]

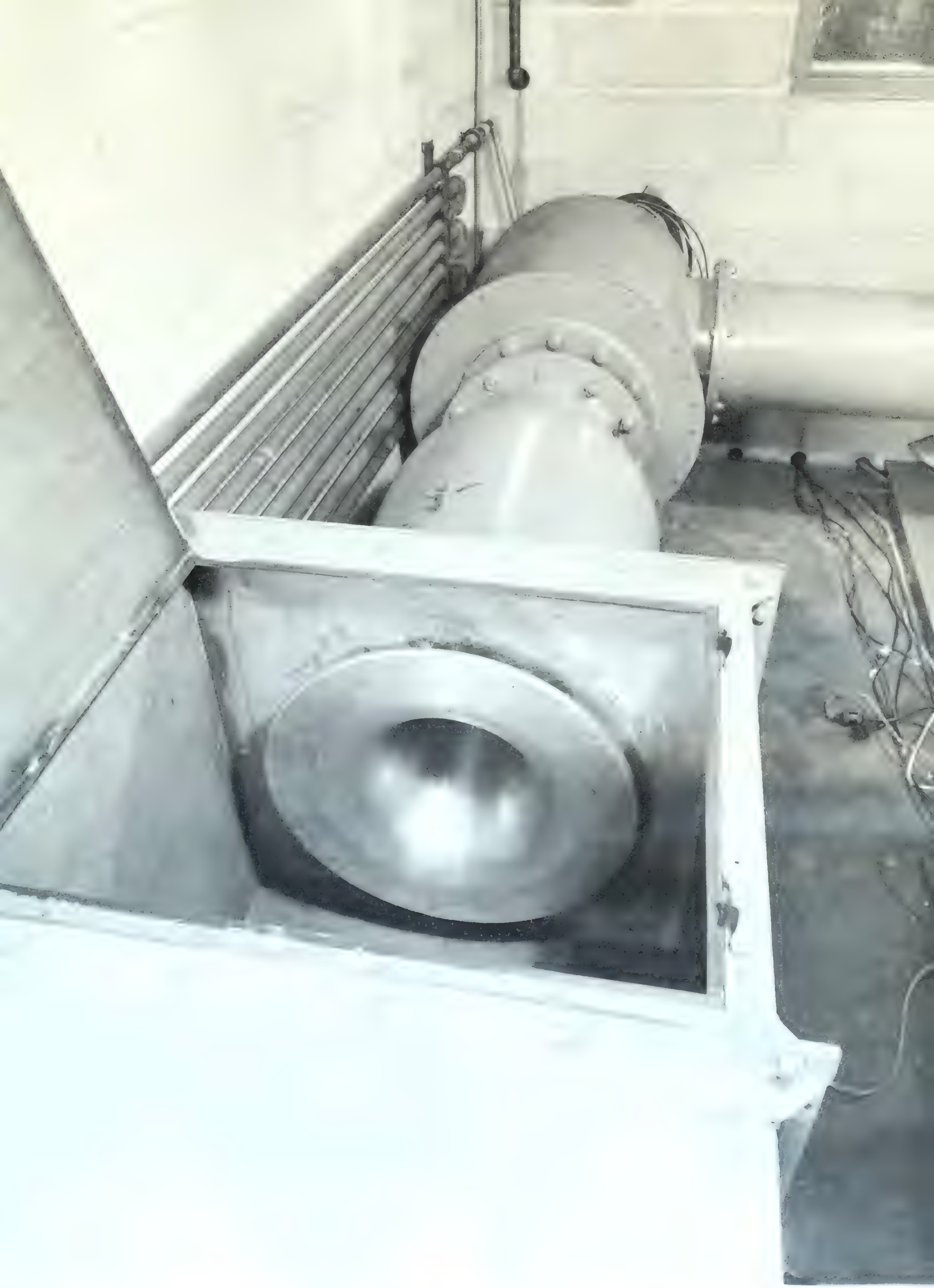


Plate VII. Compressor Measuring Orifice.

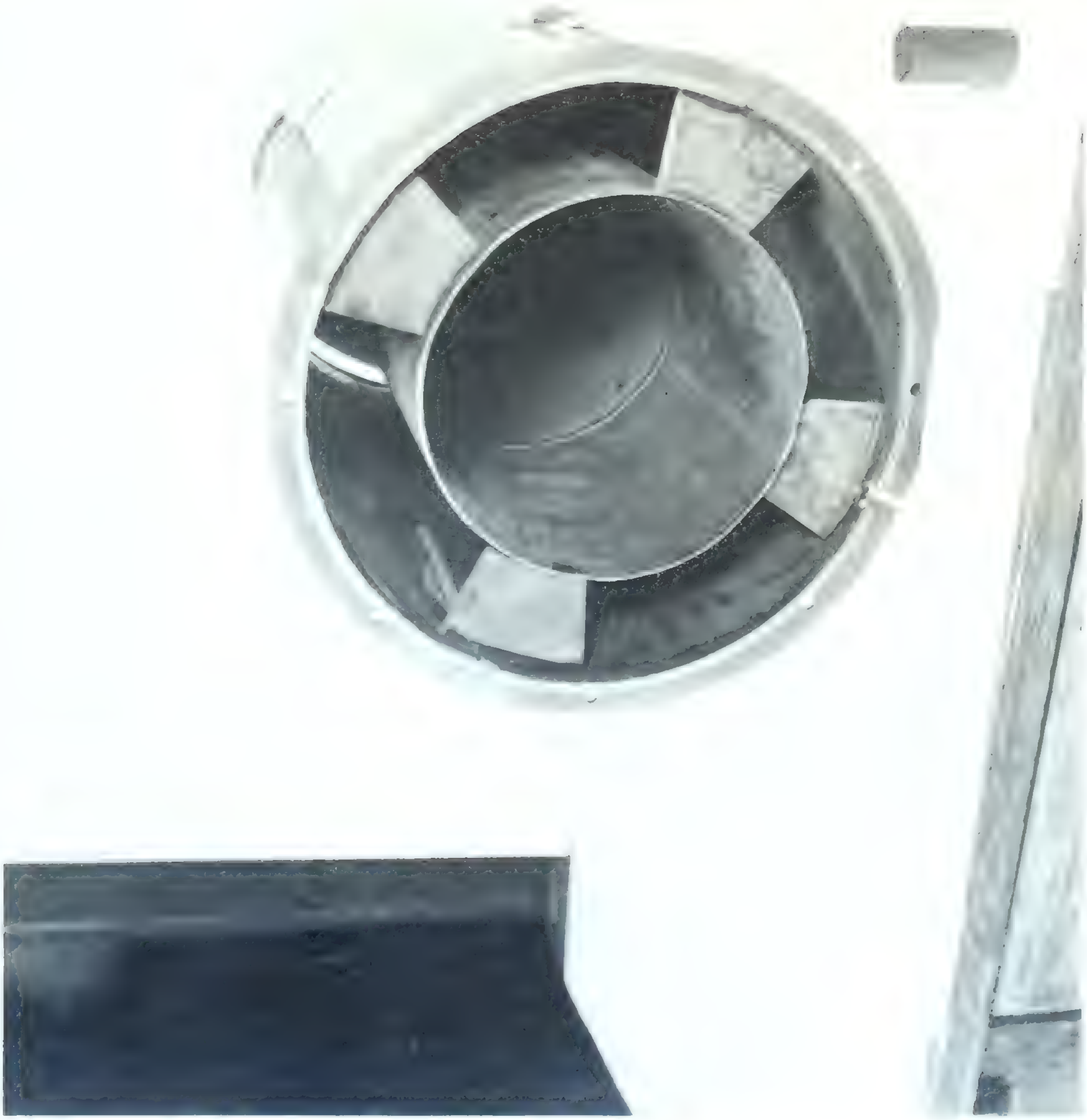


Plate XIII. Tail Pipe with Obstructions.

TABLE I

TEST DATA 19 JULY 1949

NO OBSTRUCTIONS BAROMETER 29.08 Hg

Run No.	19	20	21	22	23	24
RPM	20,000	10,000	18,000	12,000	16,000	14,000
P_{t1} "Hg	29.0	29.4	29.2	29.3	29.3	29.3
P_{T4} "Hg	19.8	5.4	16.5	7.8	12.5	9.6
P_{T5} "Hg	29.08	29.08	29.08	29.08	29.08	29.08
ΔP_t "Hg	1.76	.46	1.40	.64	1.10	.37
P_{c1} "Hg	29.08	29.08	29.08	29.08	29.08	29.08
ΔP_c "Hg	1.64	1.00	1.68	1.30	1.45	1.30
T_{t1} °F	210	152	200	175	197	138
T_{T4} °F	1312	1312	1312	1312	1312	1312
T_{c1} °F	60	60	60	60	60	60
T_{T2} °F	65	68	70	70	72	72
T_{T3} °F	260	125	230	150	203	180
Fuel flow [illegible]	[illegible]	[illegible]	[illegible]	96	113	104

TABLE II

TEST DATA 19 JULY 1949

1¼" ROD OBSTRUCTIONS AT 3.0" BAROMETER 29.06

Run No.	25	26	27	28	29	30
Rey	20,000	10,000	18,000	12,000	16,000	14,000
P_{t1}"Hg	29.1	29.4	29.2	29.4	29.2	29.3
P_{T4}"Hg	20.5	5.4	15.0	7.4	12.5	9.6
P_{T5}"Hg	29.06	29.06	29.06	29.06	29.06	29.06
ΔP_t"Hg	1.8	.50	1.40	.65	1.10	.44
P_{c1}"Hg	29.06	29.06	29.06	29.06	29.06	29.06
ΔP_c"H_2O	1.33	1.00	1.65	1.23	1.40	1.30
T_{t1}°F	200	165	200	182	200	195
T_{T4}°F	1312	1312	1312	1312	1318	1312
T_{c1}°F	60	60	60	60	60	60
T_{T2}°F	67	63	70	70	70	72
T_{T3}°F	260	125	230	150	200	130
Fuel flow #/min.	136	82	123	92	113	102

TABLE III

TEST DATA 21 JULY 1949

$1\frac{1}{4}$" DIAMETER RODS AT 2.0" BAROMETER 29.00

Run No.	31	32	33	34	35	36
RPM	10,000	20,000	12,000	18,000	14,000	16,000
P_{t1}"Hg	29.35	29.05	21.30	29.15	29.30	29.25
P_{T4}"Hg	5.3	19.3	7.3	15.5	9.5	12.5
P_{T5}"Hg	29.00	29.00	29.00	29.00	29.00	29.00
ΔP_t"Hg	.46	1.66	.66	1.38	.35	1.12
P_{c1}"Hg	29.00	29.00	29.00	29.00	29.00	29.00
ΔP_c"H_2O	1.05	1.80	1.22	1.60	1.30	1.40
T_{t1} °F	140	179	165	185	180	138
T_{T4} °F	1310	1312	1312	1318	1312	1318
T_{c1} °F	71	71	75	76	78	79
T_{T2} °F	80	82	82	90	85	88
T_{T3} °F	139	270	160	240	190	220
Fuel flow #/min.	83	139	92	123	99	117

TABLE IV

TEST DATA 22 JULY 1949

1/3 SECTOR OF TAIL PIPE
BLOCKED AT 9/16" BAROMETER 29.15

Run No.	37	38	39	40	41	42
RPM	10,000	12,000	14,000	16,000	20,000	18,000
P_{t1} "Hg	27.3	27.5	29.25	[illegible]	[illegible]	[illegible]
P_{T4} "Hg	5.6	8.1	10.5	12.8	21.1	15.8
P_{T5} "Hg	29.15	29.15	29.15	29.15	29.15	29.15
ΔP_t "Hg	.48	.67	.86	1.10	1.90	1.40
P_{c1} "Hg	29.15	29.15	29.15	29.15	29.15	29.15
ΔP_c "H_2O	1.00	1.25	1.32	1.35	1.65	1.40
T_{t1} °F	125	172	170	190	205	205
T_{T4} °F	1312	1312	1312	1310	1310	1318
T_{c1} °F	52	50	52	55	55	55
T_{T2} °F	60	60	60	62	65	65
T_{T3} °F	115	140	164	195	260	230
Fuel flow #/min.	57.5	78	116	[illegible]	130	122

TABLE V

CORRECTED TEST DATA

NO OBSTRUCTIONS COMPRESSOR

Run No.	20	22	24	23	21	19
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T3}	585	610	640	663	690	720
T_{T2}	528	530	532	532	530	525
ΔT_c	57	80	108	131	160	195
$\frac{\Delta T_c}{T_{T2}}$	.1077	.1510	.2025	.2460	.3020	.3710
θ_2	1.015	1.020	1.024	1.024	1.020	1.010
$\sqrt{\theta_2}$	1.008	1.010	1.012	1.012	1.010	1.005
P_2	24.08	22.18	19.78	17.68	15.68	13.78
δ_2	.805	.741	.661	.591	.525	.461
ΔP_c	1.00	1.30	1.30	1.45	1.68	1.62
P_{c1}	29.08	29.08	29.08	29.08	29.08	29.08
T_{c2}	520	520	520	520	520	520
$\frac{\Delta P_c P_{c1}}{T_{c1}}$	.0555	.0726	.0726	.0810	.0938	.0906
$322\sqrt{\frac{\Delta P_t P_{c1}}{T_{c1}}}$	76.0	85.7	85.7	91.6	98.5	96.9
$\frac{W\sqrt{\theta_2}}{\delta_2}$	94.7	116.7	131.4	157.0	189.2	212.0
$\frac{N}{\sqrt{\theta_2}}$	9940	11900	13800	15790	17800	19900

TABLE VI

CORRECTED TEST DATA

1¼" DIAMETER RODS AT 3.0" COMPRESSOR

Run No.	26	28	30	29	27	25
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T3}	591	610	640	660	590	720
T_{T2}	527	530	532	530	530	527
ΔT_c	54	80	108	130	160	193
$\frac{\Delta T_c}{T_{T2}}$	.1026	.1510	.2025	.2450	.3020	.3660
θ_1	1.015	1.020	1.023	1.030	[illegible]	1.115
$\sqrt{\theta_2}$	1.008	1.010	1.012	1.010	1.010	1.008
P_2	24.26	22.11	20.06	18.06	16.96	13.90
δ_2	.811	.739	.671	.604	.566	.467
ΔP_c	1.00	1.23	1.30	1.40	1.65	1.83
P_{c1}	29.06	29.06	29.06	29.06	29.06	29.06
T_{c1}	520	520	520	520	520	520
$\frac{\Delta P_c P_{c1}}{T_{c1}}$	.0559	.0639	.0728	.0784	.0924	.1023
$322\sqrt{\frac{\Delta P_c P_{c1}}{T_{c1}}}$	76.1	81.4	86.7	90.5	97.9	103.7
$W\frac{\sqrt{\theta_2}}{\delta_2}$	94.1	115.5	130.0	149.7	179.0	222.0
$\frac{N}{\sqrt{\theta_2}}$	9950	11880	13820	15850	17820	19840

TABLE VII
CORRECTED TEST DATA

1"¼ DIAMETER RODS AT 2."0 COMPRESSOR

Run No.	31	33	35	36	34	32
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T3}	599	620	650	680	700	730
T_{T2}	540	542	545	550	542	540
ΔT_c	55	78	105	130	158	190
$\frac{\Delta T_c}{T_{T2}}$	.1018	.1440	.1925	.2365	.2915	.3520
θ_2	1.033	1.042	1.049	1.058	1.042	1.034
$\sqrt{\theta_2}$	1.018	1.021	1.025	1.029	1.021	1.018
P_2	24.10	22.40	20.20	18.00	16.00	14.00
δ_2	.806	.750	.675	.602	.535	.468
ΔP_c	1.05	1.22	1.30	1.40	1.60	1.80
P_{c1}	29.00	29.00	29.00	29.00	29.00	29.00
T_{c1}	531	535	533	539	536	531
$\frac{\Delta P_c P_{c1}}{T_{c1}}$	.0572	.0662	.0702	.0753	.0865	.0982
$322\sqrt{\frac{\Delta P_c P_{c1}}{T_{c1}}}$	77.0	82.9	85.4	88.4	94.5	101.2
$\frac{w\sqrt{\theta_2}}{\delta_2}$	97.0	113.0	129.5	151.0	180.0	220.0
$\frac{N}{\sqrt{\theta_2}}$	9850	11730	13650	15450	17600	19650

TABLE VIII

CORRECTED TEST DATA

1/3 SECTOR OF TAIL PIPE BLOCKED AT 9/16" [illegible] PRESSURE

Run No.	37	38	39	40	42	41
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T3}	575	600	624	655	690	720
T_{T2}	520	520	520	522	525	525
ΔT_c	55	80	104	133	175	195
$\frac{\Delta T_c}{T_{T2}}$	.1058	.1536	.2000	.2545	.3335	.3715
θ_2	1.000	1.000	1.000	1.005	1.005	1.005
$\sqrt{\theta_2}$	1.000	1.000	1.000	1.003	1.003	1.003
P_2	24.35	22.85	19.65	17.55	15.45	13.45
δ_2	.815	.764	.657	.587	.516	.450
ΔP_c	1.00	1.25	1.32	1.35	1.40	1.65
P_{c1}	29.15	29.15	29.15	29.15	29.15	29.15
T_{c1}	512	512	512	515	515	515
$\frac{\Delta P_c P_{c1}}{T_{c1}}$	.0569	.0711	.0751	.0763	.0792	.0932
$322\sqrt{\frac{\Delta P_c P_{c1}}{T_{c1}}}$	76.7	86.0	88.3	89.0	90.6	98.5
$W\frac{\sqrt{\theta_2}}{\delta_2}$	94.0	112.5	134.1	152.0	176.0	219.5
$\frac{N}{\sqrt{\theta}}$	10000	12000	14000	15950	17940	19920

TABLE IX

CORRECTED TEST DATA

NO OBSTRUCTIONS TURBINE

Run No.	20	22	24	23	21	19
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T4}	1772	1772	1772	1772	1772	1772
θ_4	3.41	3.41	3.41	3.41	3.41	3.41
$\sqrt{\theta_4}$	1.850	1.850	1.850	1.850	1.850	1.850
P_{T4}	34.48	36.38	38.68	41.58	45.58	48.38
δ_4	1.155	1.235	1.295	1.392	1.528	1.635
P_{T5}	29.08	29.08	29.08	29.08	29.08	29.08
$\frac{P_{T4}}{P_{T5}}$	1.187	1.275	1.363	1.460	1.567	1.675
ΔP_t	.34	.52	.75	.98	1.28	1.64
P_{t1}	28.78	28.72	28.66	28.60	28.54	28.48
T_{t1}	612	635	648	657	660	670
$\frac{\Delta P_t P_{t1}}{T_{t1}}$	.0155	.0235	.0331	.0427	.0553	.0698
$565\sqrt{\frac{\Delta P_t P_{t1}}{T_{t1}}}$	70.0	86.7	102.5	116.8	132.8	[illegible]
$\frac{W\sqrt{\theta_4}}{\delta_4}$	112.2	129.2	146.4	154.8	160.5	168.5
$\frac{N}{\sqrt{\theta_4}}$	5400	6480	7256	8650	9730	10800

TABLE X

CORRECTED TEST DATA

1"½ DIAMETER RODS AT 3."0 TURBINE

Run No.	26	23	30	29	27	25
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T4}	1772	1772	1772	1776	1772	1772
θ_4	3.41	3.41	3.41	3.42	3.41	3.41
$\sqrt{\theta_4}$	1,850	1.850	1.850	1.852	1.850	1.850
P_{T4}	34.46	36.16	38.66	41.56	44.06	[illegible]
δ_4	1.154	1.220	1.293	1.390	1.472	1.660
P_{T5}	29.06	29.06	29.06	29.06	29.06	29.06
$\frac{P_{T4}}{P_{T5}}$	1.187	1.240	1.288	1.430	1.543	1.683
ΔP_t	.35	.50	.69	.95	1.25	1.65
P_{t1}	28.76	28.70	28.64	28.58	28.52	28.46
T_{t1}	635	642	655	660	660	660
$\frac{\Delta P_t \; P_{t1}}{T_{t1}}$	.0161	.0224	.0302	.0412	.0540	.0712
[illegible] $\sqrt{\frac{\Delta P_t P_{t1}}{T_{t1}}}$	[illegible]	[illegible]	[illegible]	115.0	130.4	150.0
[illegible] $\frac{\sqrt{\theta}}{\delta}$	[illegible]	127.4	139.5	[illegible]	166.0	[illegible]
$\frac{N}{\sqrt{\theta_4}}$	5400	6490	6560	8650	9740	10300

TABLE XI

CORRECTED TEST DATA

1"¼ DIAMETER RODS AT 2."0 TURBINE

Run No.	31	33	35	36	34	32
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T4}	1763	1772	1772	1772	1772	1810
θ_4	3.39	3.41	3.41	3.41	3.41	3.48
$\sqrt{\theta_4}$	1.840	1.850	1.850	1.850	1.850	1.863
P_{T4}	34.30	36.30	38.50	41.50	44.50	48.80
δ_4	1.147	1.215	1.288	1.390	1.440	1.633
P_{T5}	29.00	29.00	29.00	29.00	29.00	29.00
$\frac{P_{T4}}{P_{T5}}$	1.182	1.252	1.336	1.434	1.553	1.637
ΔP_t	.33	.53	.72	.97	1.25	1.53
P_{t1}	28.70	28.64	28.53	28.52	28.46	28.40
T_{t1}	600	625	640	643	655	630
$\frac{\Delta P_t \ P_{t1}}{T_{T1}}$	.0158	.0423	.0322	.0426	.0543	.0680
[illegible] $\sqrt{\frac{\Delta P_t P_{t1}}{T_{t1}}}$	70.3	87.8	101.0	116.2	131.0	146.8
$\frac{\sqrt{\theta_4}}{\delta_4}$	113.5	133.8	145.1	154.8	168.0	167.8
[illegible] / $\sqrt{\theta_4}$	5430	6430	7570	8650	9730	10700

TABLE XII

CORRECTED TEST DATA

1/3 SECTOR OF TAIL PIPE BLOCKED AT 9/16" TURBINE

Run No.	37	38	39	40	42	41
RPM	10,000	12,000	14,000	16,000	18,000	20,000
T_{T4}	1772	1772	1772	1764	1785	1764
θ_4	3.41	3.41	3.41	3.39	3.43	3.39
$\sqrt{\theta_4}$	1.850	1.850	1.850	1.840	1.855	1.840
P_{T4}	34.75	37.25	39.65	41.95	44.95	50.25
δ_4	1.162	1.245	1.327	1.404	1.504	1.680
P_{T5}	29.15	29.15	29.15	29.15	29.15	29.15
$\frac{P_{T4}}{P_{T5}}$	1.193	1.279	1.362	1.443	1.551	1.668
ΔP_t	.33	.52	.71	.95	1.25	1.80
P_{t1}	29.85	28.79	28.73	28.67	28.61	28.55
T_{t1}	585	632	630	650	665	665
$\frac{\Delta P_t \; P_{t1}}{T_{t1}}$	.0163	.0273	.0324	.0419	.0538	.0772
[illegible] $\sqrt{\frac{\Delta P_t P_{t1}}{T_{t1}}}$	71.8	86.6	101.1	115.0	130.5	156.5
$W \sqrt{\frac{\theta_4}{\delta_4}}$	114.0	128.7	141.1	150.5	159.8	171.5
$\frac{N}{\sqrt{\theta_4}}$	5400	6480	7565	8650	9730	10800

TABLE XIII

COMPUTED EFFICIENCY

NO OBSTRUCTIONS

Run No.	20	22	24	23	21	19
RPM	10,000	12,000	14,000	16,000	18,000	20,000
W_c	76.0	85.7	85.7	91.6	98.5	96.9
T_{T2}	528	530	532	532	530	525
C_pT_{T2}	126.8	127.1	127.8	127.8	127.1	126.0
$\frac{\Delta T_c}{T_{T2}}$	.1979	.1510	.2025	.2460	.3030	.3719
L_c	1038.0	1648.0	2215.0	2375.0	3840.0	4530.0
W_t	70.0	86.3	102.5	116.5	132.5	143.7
T_{T4}	1772	1772	1772	1772	1772	1772
C_pT_{T4}	482.0	482.0	482.0	482.0	482.0	482.0
$1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}$	.0415	.0580	.0737	.0888	.1063	.1150
L_t	1400.0	2410.0	3645.0	5050.0	6800.0	8250.0
η_t	74.3	68.3	62.5	56.9	56.4	54.9
$C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]$	20.0	27.9	35.5	42.8	51.3	55.4
$224\sqrt{C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]}$	1000.0	1183.0	1335.0	1466.0	1605.0	1617.0
.0480	480.0	576.0	672.0	768.0	864.5	960.0
$\frac{U}{C}$	.480	.483	.503	.523	.537	.593

TABLE XIV

COMPUTED EFFICIENCY

1"½ DIAMETER RODS AT 3."0

Run No.	26	28	30	29	27	25
RPM	10,000	12,000	14,000	16,000	18,000	20,000
W_c	76.0	84.4	86.7	89.5	97.8	103.2
T_{T2}	527	530	532	530	530	527
c_pT_{T2}	126.5	127.8	127.8	127.2	127.2	126.5
$\frac{\Delta T_s}{T_{T2}}$	.1026	.1510	.2025	.2450	.3020	.3660
L_c	938.0	1618.0	2240.0	2805.0	3755.0	4780.0
W_t	71.4	84.0	97.8	114.0	130.8	150.0
T_{T4}	1772	1772	1772	1778	1772	1772
c_pT_{T4}	432.0	432.0	432.0	434.0	432.0	432.0
$1-\frac{1}{P_R^{\frac{\gamma-1}{\gamma}}}$	.0415	.0515	.0605	.0849	.1020	.1235
L_t	1427.0	2083.0	2855.0	4655.0	6480.0	8945.0
η_t	68.3	77.4	77.6	52.5	57.3	53.5
$c_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]$	20.0	24.8	29.2	40.9	49.5	59.6
$224\sqrt{c_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]}$	1002.0	1115.0	1210.0	1432.0	1576.0	1729.0
.048N	480.0	576.0	672.0	768.0	846.5	960.0
$\frac{U}{C}$	.480	.516	.555	.537	.547	.555

TABLE XV

COMPUTED EFFICIENCY

1"½ RODS AT 2."0

Run No.	31	33	35	36	34	32
RPM	10,000	12,000	14,000	16,000	18,000	20,000
W_c	77.0	82.9	85.4	88.4	94.5	101.2
T_{T2}	540	542	545	550	542	540
C_pT_{T2}	129.7	130.2	131.0	132.1	130.2	129.7
$\frac{\Delta T_c}{T_{T2}}$	.1018	.1440	.1925	.2365	.2915	.3520
L_c	1015.0	1556.0	2150.0	2765.0	3590.0	4620.0
W_t	70.8	87.7	101.0	116.2	130.0	146.8
T_{T4}	1763	1772	1772	1772	1772	1810
C_pT_{T4}	429.0	432.0	432.0	432.0	432.0	494.0
$1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}$	.0412	.0540	.0690	.0852	.1040	.1232
L_t	1397	2285	3360	4770	6575	8940
η_t	72.7	68.0	63.9	58.0	54.5	51.3
$C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]$	19.7	26.0	33.3	41.0	50.1	59.4
$\sqrt{C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]}$	994.0	1142.	1290.	[illegible]	[illegible]	[illegible]
.048N	480.0	576.0	672.0	768.0	864.5	960.0
$\bar{C}$	.482	.503	.521	.535	.545	.555

TABLE XVI

COMPUTED EFFICIENCY

1/3 SECTOR OF TAIL PIPE BLOCKED AT 9/16"

Run No.	37	38	39	40	42	41
RPM	10,000	12,000	14,000	16,000	18,000	20,000
W_c	76.7	86.0	88.3	89.0	90.6	98.5
T_{T2}	520	520	520	522	525	525
C_pT_{T2}	124.7	124.7	124.7	125.2	126.0	126.0
$\frac{\Delta T_c}{T_{T2}}$	.1058	.1536	.2000	.2545	.3335	.3715
L_c	1010.0	1646.0	2175.0	2840.0	3800.0	4610.0
W_t	71.8	86.6	101.1	115.0	130.5	156.5
T_{T4}	1772	1772	1772	1754	1785	1764
C_pT_{T4}	432.0	432.0	432.0	479.3	436.0	479.3
$1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}$	.0429	.0590	.0732	.0878	.1058	.1208
L_t	1480.0	2460.0	3570.0	4830.0	7670.0	9055.0
η_t	68.2	66.8	60.9	53.8	49.5	51.0
$C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]$	20.6	28.4	35.3	42.7	51.5	57.9
$4\sqrt{C_pT_{T4}\left[1-\frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}\right]}$	1015.0	1200.0	1319.0	1462.0	1608.0	1705.0
.048N	480.0	576.0	672.0	768.0	864.5	960.0
$\frac{U}{C}$	.473	.480	.505	.523	.537	.563

TABLE XVII

EFFICIENCY BY CURVES

RPM	10,000	12,000	14,000	16,000	18,000	20,000
$\frac{N}{\sqrt{\theta_2}}$	9935	11878	13818	15760	17790	19828
$\frac{W\sqrt{\theta_2}}{\delta_2}$	94.0	113.0	132.8	152.0	178.2	217.0
$\sqrt{\theta_2}$	1.010	1.020	1.014	1.013	1.010	1.009
δ_2	.801	.733	.666	.602	.542	.473
R_c	76.0	81.7	87.4	90.4	95.8	102.0
T_{t2}	529	531	532	534	532	529
$c_p T_{t2}$	127.0	127.5	127.7	128.2	127.7	127.0
$\frac{\Delta T_c}{T_{t2}}$	.1016	.1502	.1970	.2420	.3000	.3700
W_c	975.0	1560.0	2195.0	2300.0	3670.0	4785.0
$\frac{N}{\sqrt{\theta_4}}$	5408	6433	7563	8650	9733	10775
$\sqrt{\theta_4}$	1.850	1.850	1.850	1.850	1.850	1.850
δ_4	1.150	1.212	1.307	1.414	1.510	1.640
$\frac{W\sqrt{\theta_4}}{\delta_4}$	112.0	130.0	144.5	155.0	161.5	168.5
R_t	69.6	85.1	102.0	118.6	132.0	149.5
T_{t4}	1770	1772	1772	1772	1776	1778
$c_p T_{t4}$	431.2	432.0	432.0	432.0	433.4	434.0
$1 - \frac{1}{P_{RT}^{\frac{\gamma-1}{\gamma}}}$	[illegible]	.0252	.0702	.0896	.1030	.1182
W_t	1160.0	2150.0	3460.0	5140.0	6560.0	8550.0
η_t	77.5	72.5	63.5	54.5	55.9	56.0

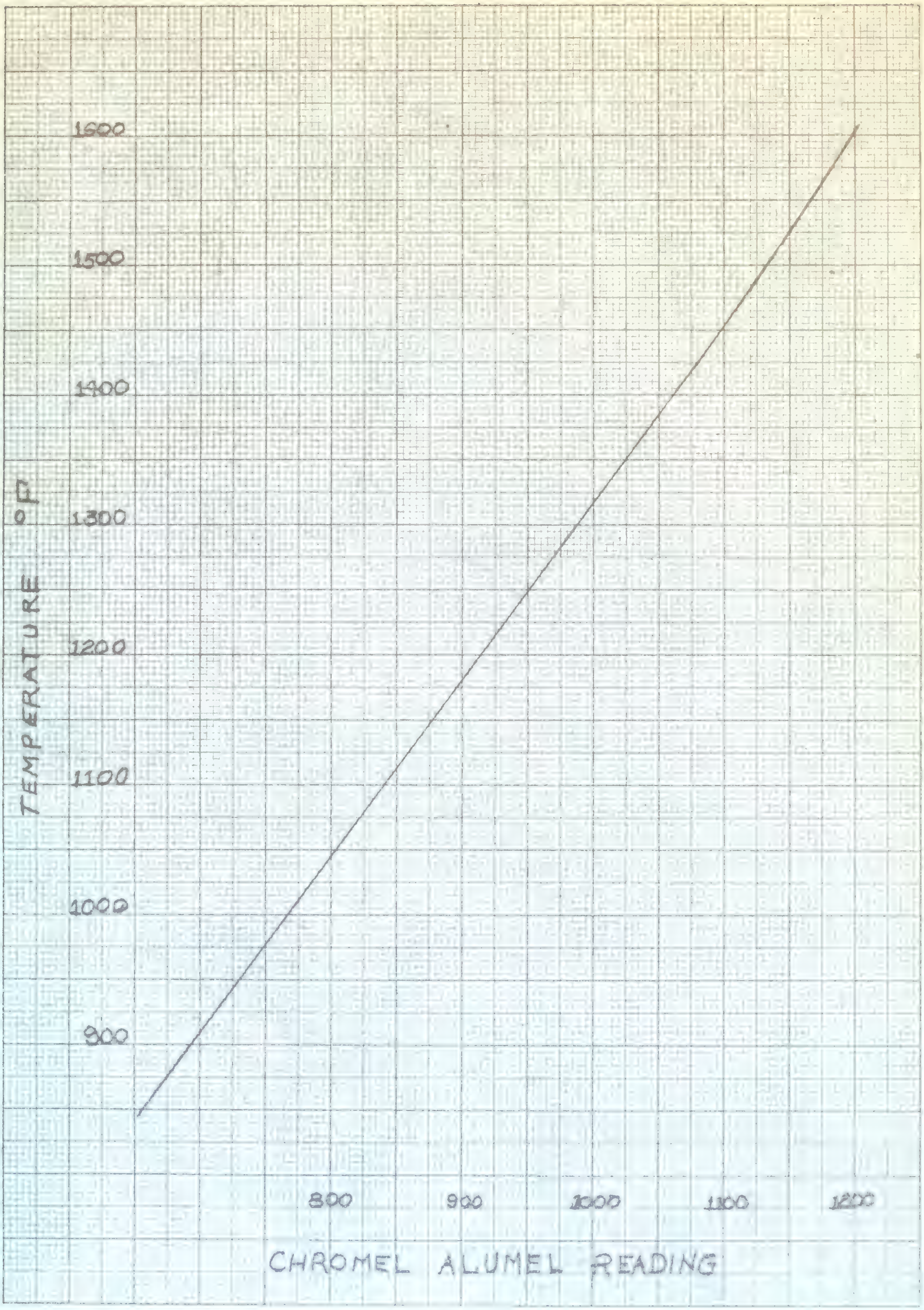
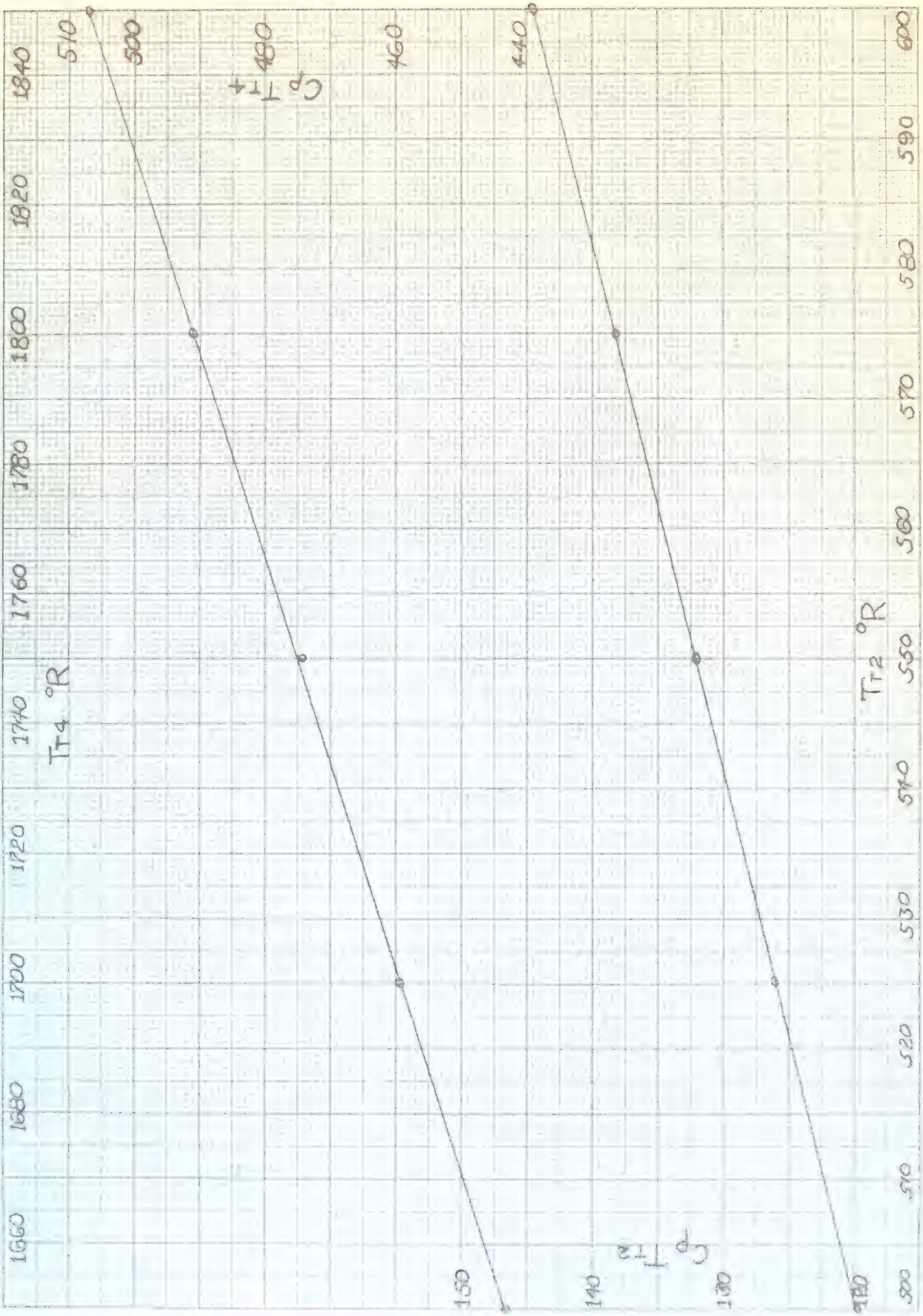


Fig. 1 Chromel Alumel Correction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480
460
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$C_p T_2$
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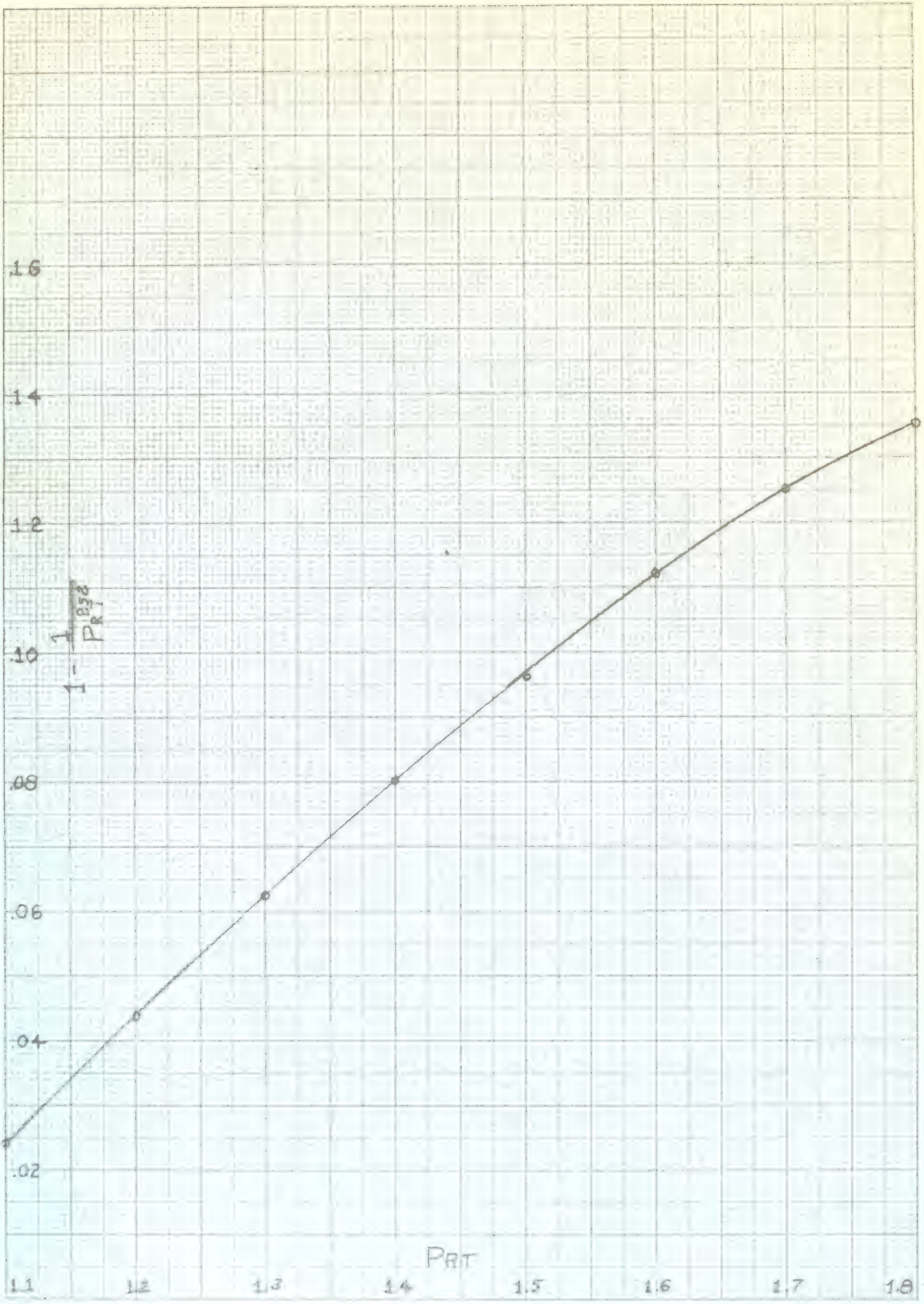
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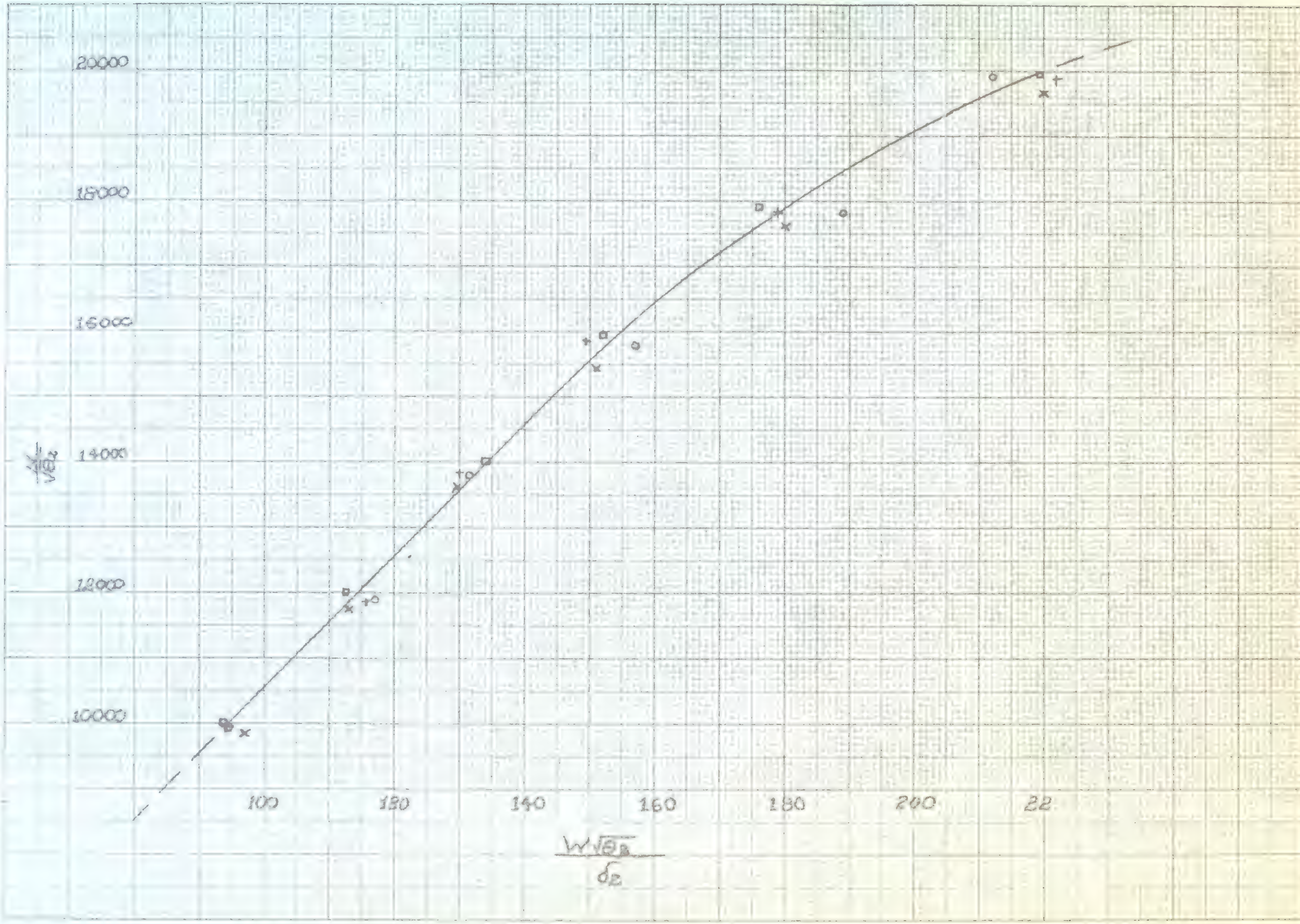
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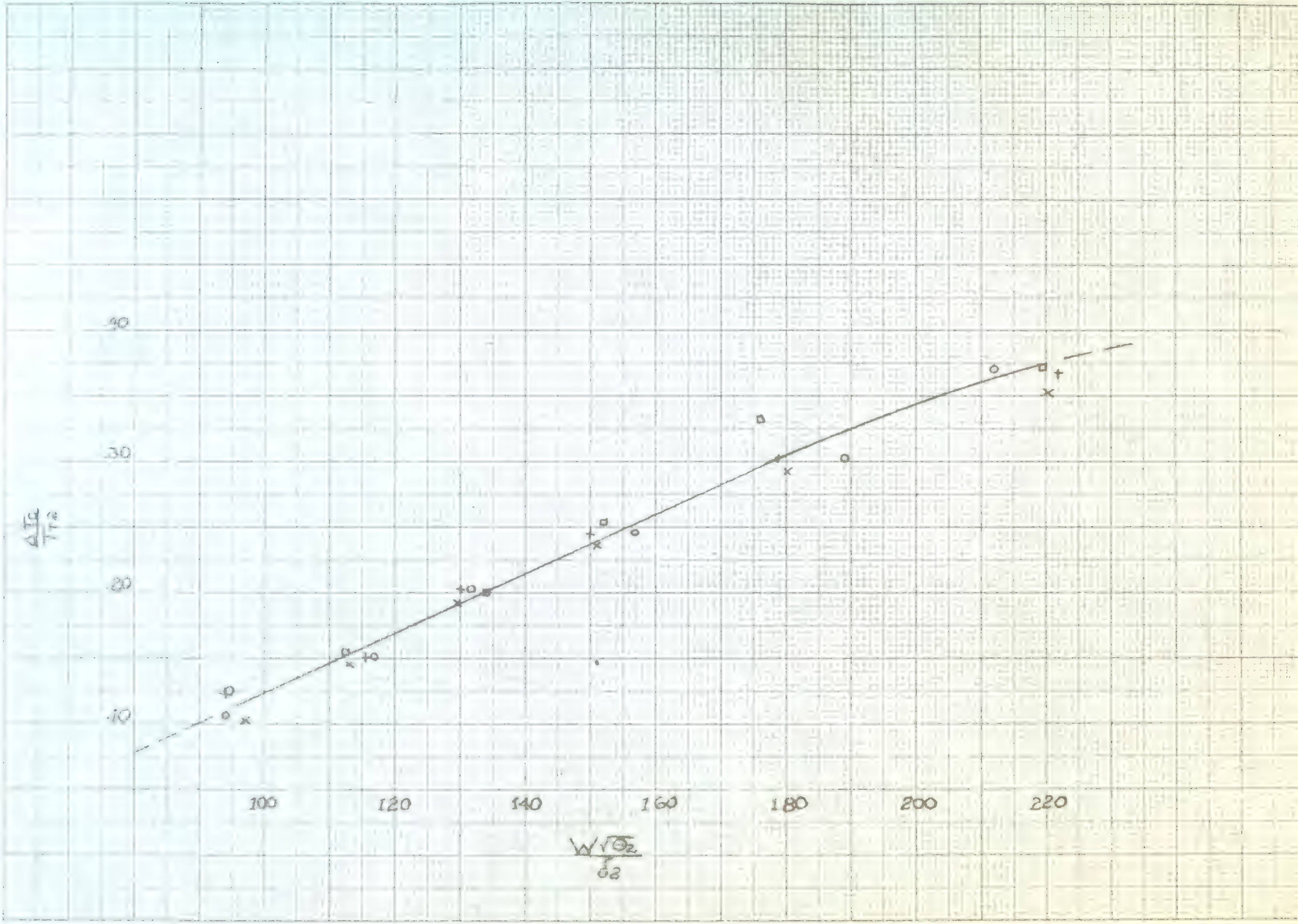
Fig. [illegible]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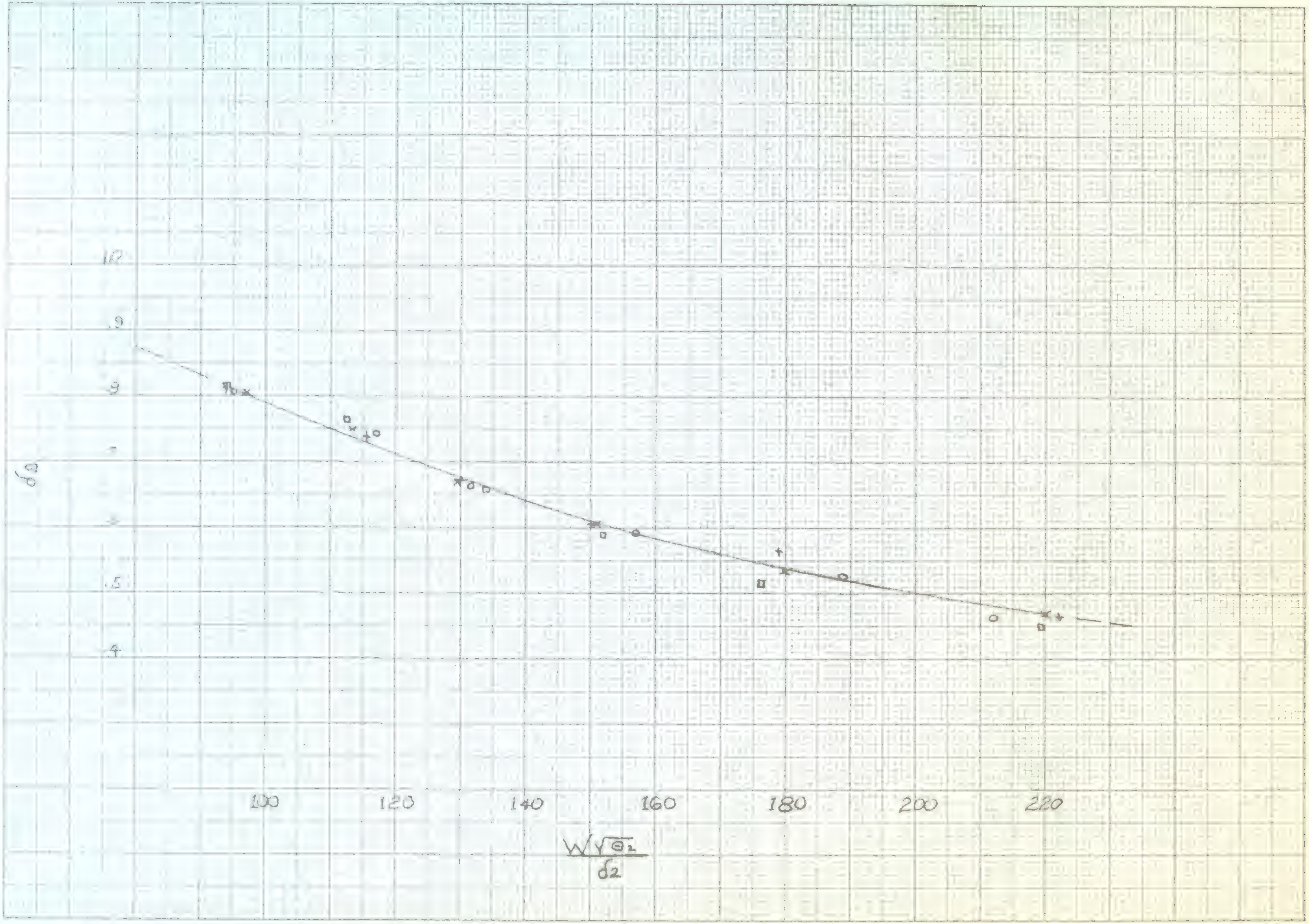
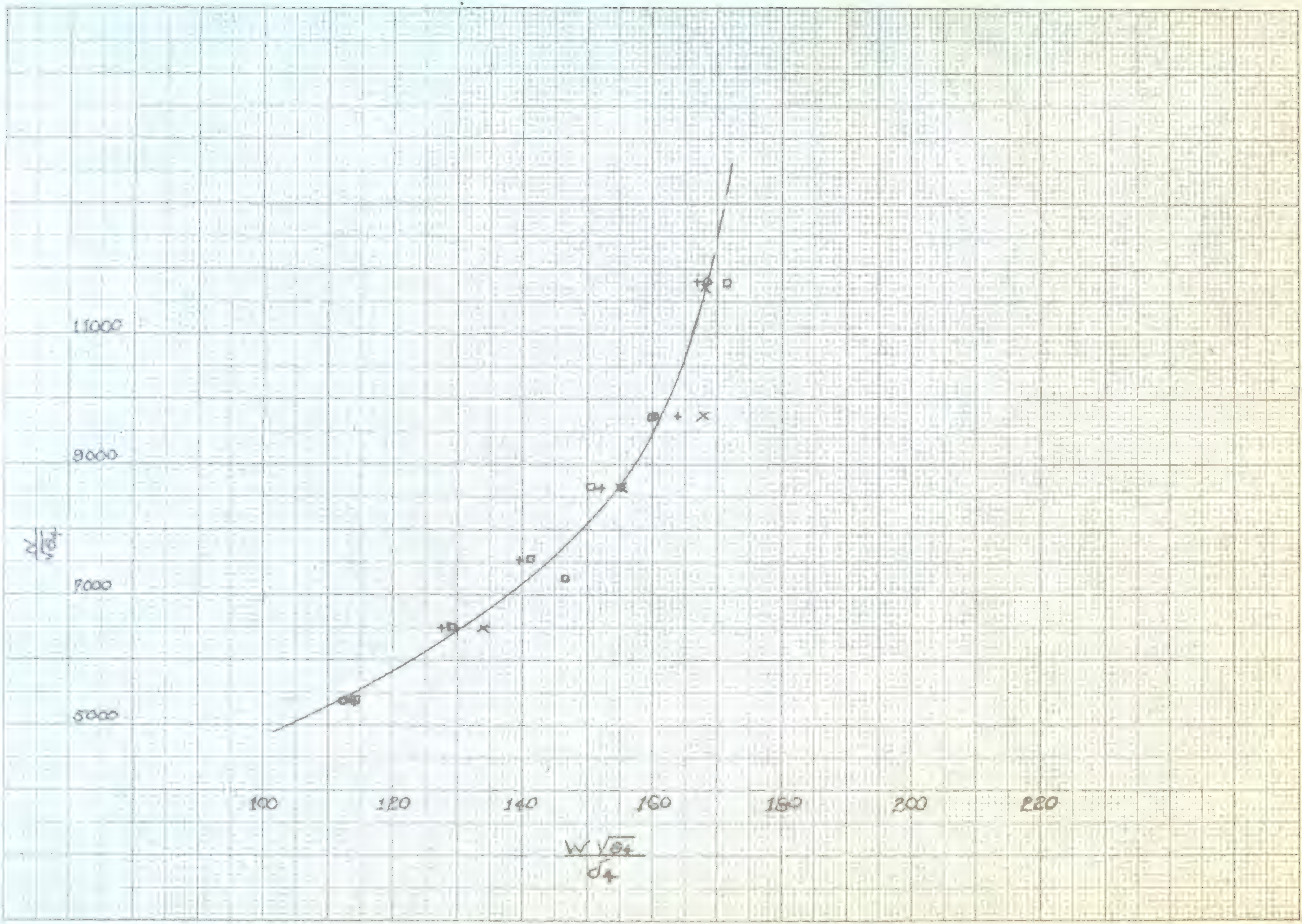
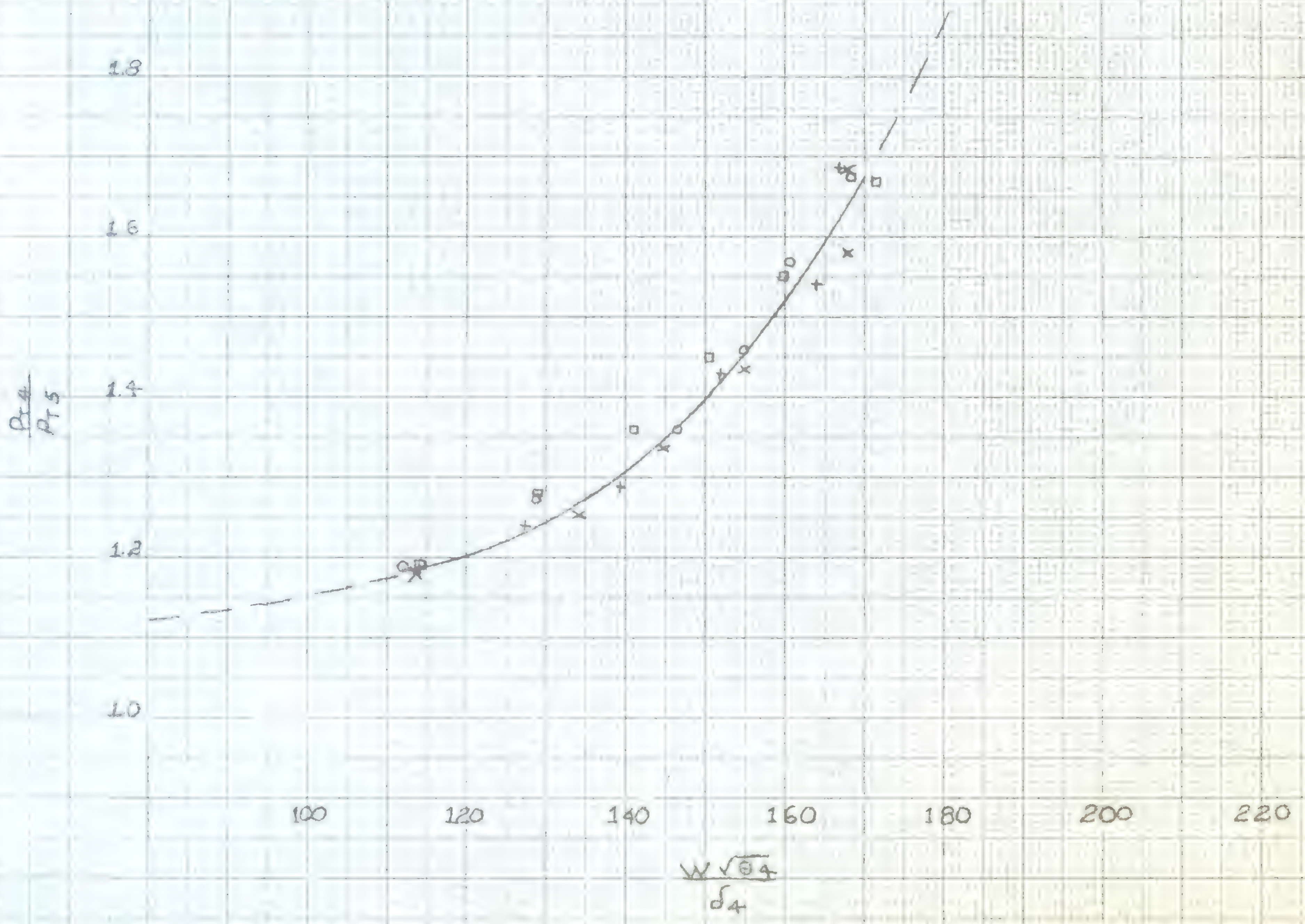
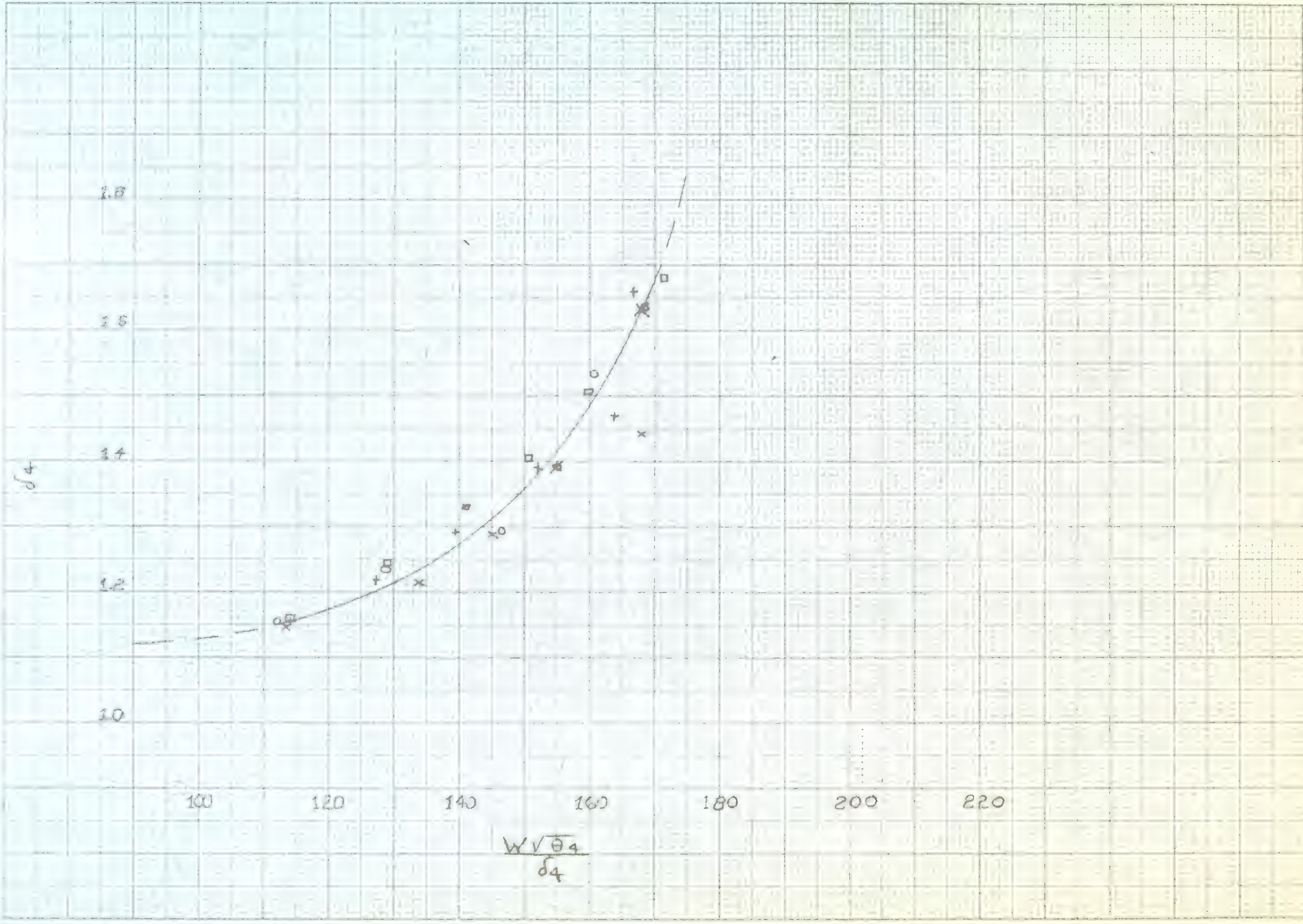
$\frac{\Delta T_2}{T_{r2}}$
100
120
140
160
180
200
220
$\frac{W\sqrt{\Theta_2}}{\delta_2}$


1.0
.9
.8
.7
.6
.5
.4
δ0
100
120
140
160
180
200
220
$\frac{W\sqrt{\theta_2}}{\delta_2}$


11000
9000
7000
5000
$\frac{N}{\sqrt{\theta_4}}$
100
120
140
160
180
200
220
$\frac{W\sqrt{\theta_4}}{\delta_4}$


1.8
1.6
1.4
1.2
1.0
$\frac{p_{T4}}{p_{T5}}$
100
120
140
160
180
200
220
$\frac{W\sqrt{\theta_4}}{\delta_4}$



1.8
1.6
1.4
1.2
1.0
δ_4
100
120
140
160
180
200
220
$\frac{W\sqrt{\theta_4}}{\delta_4}$

DATE DUE

Thesis 11470
S668 Spencer
An experimental study of the influence of obstructions immediately downstream from the turbine wheel on turbine performance.

Thesis 11470
S668 Spencer
An experimental study of the influence of obstructions immediately downstream from the turbine wheel on turbine performance.

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